MAGNETODYDRODYNAMIC POWER GENERATION FOR NUCLEAR-

POWERED SEA-GOING VESSELS

by

Joseph Dwight Hutchinson

Lieutenant, U. S. Navy

B.S. United States Naval Academy 1958

Submitted in Partial Fulfillment

of the

Requirements for the Professional Degree of

Naval Engineer

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Department of Naval Architecture and Marine Engineering, May 20, 1966

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Thesis Supervisor

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Chairman, Departmental Committee on Graduate Students

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Submitted to the Department of Naval Architecture and Marine Engineering on May 20, 1966, in partial fulfillment of the requirements for the Professional Degree of Naval Engineer and for the degree of Master of Science in Electrical Engineering.

ABSTRACT

This thesis is intended as an initial feasibility study to determine whether the advantages offered by an MHD conversion system are worth further investigation. Two MHD power cycles are analyzed - a gas Brayton cycle and one example of a liquid-metal Rankine cycle. The significant results are that the potential of MHD power generation is excellent for the reduction of noise, and that future developments will undoubtable increase the cycle efficiencies to competitive levels. The Rankine cycle appears to be superior to the Brayton cycle in all major respects with the exception of producing the least noise. The Brayton cycle, because of low electrical conductivity in the working fluid, requires the use of superconducting magnets, and the refrigeration power requirement for these coils will reduce markedly the efficiency of this cycle. Low terminal voltages hinder the Rankine cycle with a D-C MHD generator, but this cycle possesses the advantage of the possibility of direct A-C power generation from an MHD induction generator which eliminates the low voltage problem.

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NOMENCLATURE

SYMBOL	DESCRIPTION
A	Cross sectional area of generator flow channel
B	Magnetic field
C_p	Gas specific heat at constant pressure
C_v	Gas specific heat at constant volume
E	Electric field intensity
g	Gravity constant
H	Height of generator flow channel
h	Enthalpy per unit mass of working fluid
I	Current from generator
J	Current density
K	Generator loading factor ($K = -E/vB$)
L	Length of generator flow channel
m	Mass of working fluid
p	Pressure
P_e	Electrical power density
P_{req}	Total electrical power required from generator
Q	Heat (supplied or rejected) per unit mass
R	Perfect gas constant
S	Entropy per unit mass
T	Temperature of working fluid
v	Velocity of working fluid
v_s	Induction generator phase velocity
V_t	Terminal voltage of generator
X	Quality of working fluid
x,y,z	Coordinates

SYMBOL	DESCRIPTION
γ	Specific heat ratio, $= C_p/C_v$
η_{cyl}	Cycle efficiency
η_d	Diffuser efficiency
η_g	Generator efficiency
η_n	Nozzle efficiency
ρ	Density
σ	Electric conductivity
α	Void volume fraction

SUBSCRIPTS

L	Liquid
V	Vapor
0,1,2,3,4,5,	Thermodynamic states of working fluid

Chapter I

INTRODUCTION

1.1 Background

One of the current problems in submarine and antisubmarine warfare vessels is the minimization of radiated noise. On nuclear-powered ships a large fraction of this noise is generated by the steam turbines used to provide the ship's propulsive power and the ship's "hotel" power (i.e. electrical power for lights, radar, sonar, etc.). If electric motors, rather than turbines, could be used for these purposes, much of this radiated noise would be eliminated. Furthermore, since for all practical purposes, effective future development of the steam cycle is rapidly nearing an end (in terms of improved efficiency), it seems reasonable to investigate other means of converting nuclear energy to electrical energy that would meet the need for quieter operation at little, or no, loss in efficiency.

One possible method of accomplishing this conversion is to couple a magnetohydrodynamic generator to a nuclear reactor utilizing either a Brayton or a Rankine thermodynamic cycle. Magnetohydrodynamics, or MHD, uses a magnetic field to convert energy between hydrodynamic and electrical forms. It had its beginning in the 19th century when Faraday [(1)*] discovered that a conductor moving in a magnetic field could be made to generate an electric current, which is the principle that has traditionally been applied to electric motors and generators. Faraday also made an attempt, in 1831, to measure experimentally the electromechanical interaction due to the flow of the River Thames in the Earth's magnetic field.[(1)] Although unsuccessful, due to polariza-

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* Superscript numerals refer to the list of references

tion of the electrodes, he set forth the basic principles of MHD conversion which are applicable today. Another pioneer was Northrup,[2] who studied experimentally in the early 1900's the interaction of a current and a magnetic field in a liquid conductor and found that the passage of a current through mercury in an open tray caused a V-shaped depression to form in the center. He suggested this phenomenon ("pinching effect") as the basis for achieving motion without the use of brushes or slip rings.

Development of the electromagnetic pump began around the time of the First World War. In 1915, Chubb [3]proposed an induction pump for liquid-metals, and in 1919, Petersen[4] proposed the MHD conduction generator, using ionized gas as an armature.

The interwar period saw simple laboratory experiments being performed by such men as Williams[5] and Hartmann.[6] In 1928, Einstein and Szilard[7] suggested an electromagnetic pump using an alkali metal for a refrigeration cycle. Shortly thereafter, Alfvén,[8] after much experimentation, published his classic paper on magnetohydrodynamics which further aroused the interest of the science-world.

After the Second World War, the development of MHD pumps reached the state where their use in pumping liquid metal coolants for nuclear reactors became standard practice. These pumps have the very desirable feature of requiring no penetration into the liquid-metal and makes complete sealing possible. Their size and weight are also of the same order of magnitude as mechanical liquid-metal pumps of the same rating.

In the past decade, the MHD generator in a power cycle has attracted increased interest. Initially, this interest was focused on

the possibility of using the MHD generator in a topping cycle for fossil fuel central power stations, and later on the possibility of coupling the generator with a nuclear reactor in a closed cycle for use either in space applications or in large land power employment.[9] There has even been considerable research concerning the use of an open-cycle MHD system to power rockets utilizing a combustion-gas plasma as the working fluid.[10] For ships, however, there has been little interest, despite such readily apparent advantages as: (a) the possibility of generating less noise; (b) the simplicity of a structure with no rigid moving parts; (c) the possibility of higher efficiencies than present-day steam cycles; (d) the possibility of weight and volume reductions; and (e) the proven workability of the same principles in electromagnetic pumps. This paper, therefore, will take a closer look at the possibility of utilizing a closed-cycle MHD power system for nuclear-powered sea-going vessels.

If a closed cycle is specified, as required for ships, either a pure vapor Brayton cycle or a condensing Rankine cycle would be utilized using the reactor coolant as the generator's working fluid. The fluid for a Brayton cycle, if a gas (i.e. helium), would require seeding with an alkali metal to promote its electrical conductivity, which would be further increased through the generator due to ionization effects. If a metal vapor is used, the lowest system temperature must remain higher than the metal's condensing temperature and, again, ionization effects must be present to achieve sufficient electrical conducticity. In the condensing Rankine cycle, a liquid-metal would be used with the liquid in the generator, essentially eliminating the conductivity problem. In this paper the ramifications of each cycle and its possible application to sea-going vessels will be described in more detail.

1.2 Object and Scope of This Study

The purpose of this thesis is to examine the feasibility of integrating an MHD generator with a nuclear reactor, with the ultimate objective of adapting this system to satisfy the power requirements of a sea-going vessel. The primary stimulus of this investigation was derived from the present noisy marine propulsion systems, but this, however, does not restrict the forthcoming analysis from other applications of such generation systems.

The remainder of this chapter is used to estimate the type and amount of power required for a typical nuclear-powered ship, describe briefly the principles of an MHD generator, and discuss in more detail the possible MHD power cycles which could be used. A typical Brayton cycle, with particular emphasis given to the MHD generator, is described and analyzed in chapter 2. Chapter 3 will include a description of a typical Rankine cycle, a discussion of several different proposed liquid-metal energy conversion systems, and an analysis of one of the systems. A comparison between the two cycles and a brief look at the shipboard integration problem composes chapter 4. Appropriate conclusions and recommendations are in chapter 5.

Because of the large scope of the problem, this thesis is intended only as a preliminary feasibility study to determine whether or not the subject is worth further investigation. As will be shown, it is believed that this thesis will provide some of the foundation for future analyses.

1.3 Establishment of the Demand

With the exception of giant aircraft carriers and fast merchant ships, nuclear-powered vessels generally require about 15,000 horsepower or, equivalently, 11 megawatts of eletrical power.[11] Most of this power is for

the propulsion requirements, while a small amount (generally A-C) is required for ship services (i.e. lights, communications, auxiliary machinery, etc.). If an MHD power cycle is to be used, suitable electric motors must also be available for propulsive purposes and for inversion to A-C power (if D-C is the only output from the MHD machine). These motors would have numerous advantages over turbine drives such as lower maintenance, elimination of gearing, easier methods of reversing power, more freedom in the location of the prime power source, and quieter operation. Moreover, previously conducted studies[12,13] have indicated the possibility of utilizing electrical motors at this high power level (11 megawatts) and have suggested that either D-C or A-C types would be entirely satisfactory.

Thus, for the purposes of this study, the output power from the MHD device will be in the neighborhood of 11 megawatts and both A-C and D-C generators will be considered as possible power sources.

1.4 MHD Principles

The principles of MHD generators are basically simple. Figure I is a schematic representation of the elementary D-C MHD generator. Fluid from a high-pressure source flows from left to right (y-directed) through the channel. A magnetic field is applied perpendicular to the direction of the fluid motion (z-directed), and an EMF is induced in the third mutually perpendicular direction (x-directed). If the fluid is an electrical conductor, current may be tapped from the fluid flow by the electrodes and fed to an external load. The action is similar to that of a conventional generator in which a copper conductor is rotated in a magnetic field. When a current is drawn from a conventional generator, a torque is required to rotate the wire in the field.

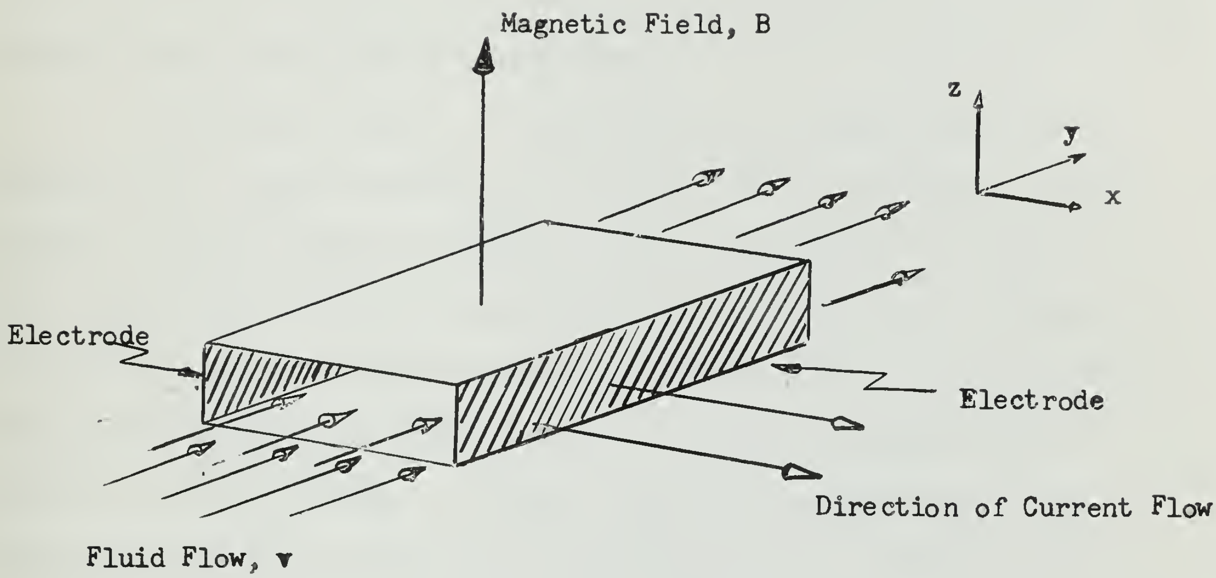

Figure I (Schematic of MHD Generator)

For the MHD generator, a pressure difference is needed to force the fluid through the generator's field when a current is drawn. This, of course, is accomplished thermodynamically, where the operation of the MHD generator from the standpoint of a heat engine cycle is identical to that of a gas turbine. Useful work is extracted from the fluid flow at the expense of pressure and enthalpy drops.

The trait that categorizes MHD generators is that a body force, rather than a surface force or effect, is directly involved in the transformation process. Referring to Figure I, the electrical power density, Pe, is equal to the product EJ, where E is the electric field strength and J the current density of the working fluid. Since, according to Ohm's Law, $J = \sigma(E + vB)$ for the moving fluid, the power density is:

$$Pe = EJ = -\sigma(vB)^2 K\ (1-K)$$

where B is the applied magnetic field, v is the fluid velocity, σ is the fluid conductivity, and K ($= -E/vB$) is the machine loading factor. This quantity is directly related to the ratio of electrical power supplied for the externally connected load to the total generated power.

Referring to Figure I, the geometry is naturally suited to D-C operation and it seems reasonable to consider that as the type of output. However, as will be shown in chapters 2 and 3, the output D-C voltage is quite low and other means are therefore sought to resolve this problem. Since the voltage is equal to the product $K\bar{W}vB$ where $\bar{W}$ is the mean width between the electrodes, a possible method is simply to adjust one, or several, of these parameters. However, since this variation will also change the total power output, the low voltages must be accepted if D-C is desired for a given power requirement. Thus, because of this and because A-C power is a desirable output, a brief look at the possibilities of an A-C MHD generator seems reasonable.

A straightforward way of producing the A-C power is by alternating the magnetic field. This, however, does not improve the low voltages generated and, since the peak voltage is the same, the power density is only half as great.[9] Jackson and Pierson,[14] however, have suggested an induction generator which permits higher voltages through increased windings and eliminates the need for electrodes. Interestingly, previous studies on marine propulsion systems have also investigated induction motors for powering a ship and found them to be a most satisfactory possibility.[12] In slightly more detail, an analysis of this type of generator will be included in chapter 3, but within the limitations of this study it is not possible to consider fully the induction generator. However, the direct generation of A-C is an advantage, and it should be seriously considered in future studies. It is worthwhile to mention that previous work has shown that the induction generator is only feasible with high-conductivity liquid-metals of the Rankine cycle.[14]

1.5 Discussion of Possible MHD Power Cycles

Figure II illustrates the essential components of a closed cycle utilizing an MHD generator to convert heat into electrical energy. The fluid

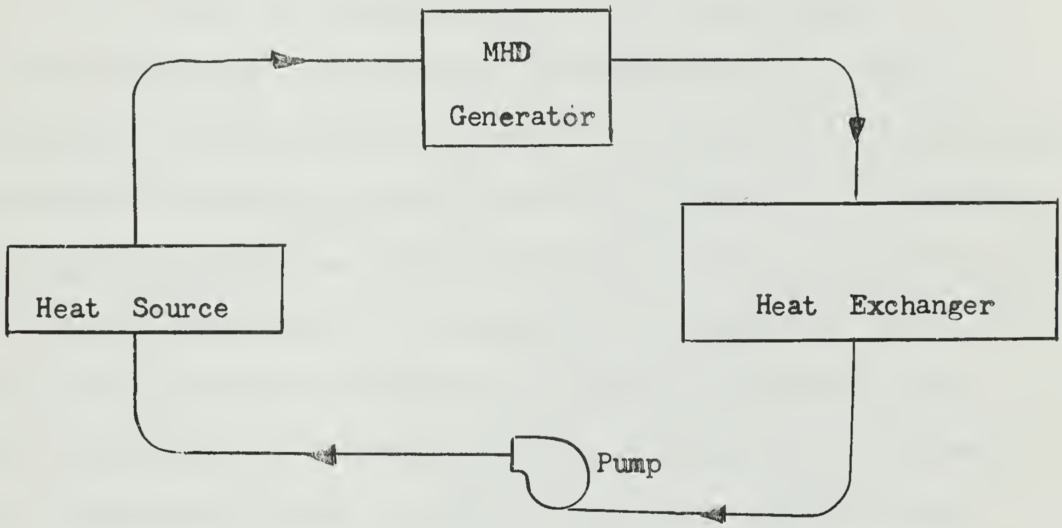

Figure II (MHD Power Cycle)

is passed through the energy-conversion MHD generator, then through a heat exchanger, and finally pumped back to the heat source. This basic cycle is described in more detail in chapters 2 and 3, where the Brayton cycle's working fluid is a vapor throughout the cycle and the Rankine cycle's working fluid utilizes a liquid-vapor mixture through at least part of the cycle.

From the previous section, the power density $\left[= \sigma (vB)^2 K(1 - K)\right]$ relation demonstrates that the product σv^2 essentially determines the type of fluid to be used. In the vapor (or Brayton) MHD cycle serious technological problems exist with the attainment of adequate electrical conductivity of the fluid within the temperature restrictions imposed by reactor considerations and the available materials.[15] In the condensing (or Rankine) cycle, the conductivity problem does not exist, although the velocities attainable are

much less if a liquid-metal is used in the generator. Hence, as far as comparing the two systems from the power density relation, there appears to be no serious difference.

If a Brayton cycle is used, cesium-seeded helium would be a common fluid. The electrical conductivity of this plasma, however, is far too low at the present reactor temperatures (~1500°K) unless a scheme to raise its electrical conductivity is utilized.[9] At present an extra-thermal (or nonequilibrium) ionization process in which the electric field produced by motional induction raises the electron temperature in the gas higher than the equilibrium gas temperature, is the most satisfactory scheme used.[16,17] The Brayton cycle requires a very efficient compressor to pump the gas to the heat source and this compressor would most certainly rob the MHD generator of substantial amounts of power. A further derogatory effect found from the analysis in chapter 2 is that in order to obtain the required power output from the gas MHD generator, extremely high levels of the applied magnetic field are needed, indicating super-conducting magnets. The refrigeration requirement for these magnets, although not calculated, is expected to be very high and will probably degrade the cycle efficiency to unacceptable levels.[18]

If a condensing (or Rankine) cycle is used, a compressor would not be required. The liquid-metal cycle, however, does require either some means of converting thermal energy to liquid kinetic energy (and this friction surface is an unwanted item in any cycle), or else running a two-phase flow through the generator (which creates conductivity problems). An advantage over the vapor system, though, is the potential the liquid-metal cycle possesses for the possibility of direct A-C power generation.[19]

The question then arises as to whether a Rankine cycle system utilizing a liquid-metal in the generator duct, or a Brayton cycle system using a gas, is most desirable. In the next three chapters a Brayton cycle is described and analyzed, several schemes of Rankine cycles are described, one of them is analyzed, and their cycle analyses are compared as to their worth for possible future uses.

Chapter II

ANALYSIS OF A BRAYTON-CYCLE MHD POWER SYSTEM

2.1 General Description

The ideal Brayton cycle consists of two reversible constant-pressure processes and the two reversible adiabatic processes, as shown in Figure III where the numbers indicate the different thermodynamic states and correspond to the MHD cycle of Figure IV. A reciprocating engine operating on this cycle, developed by George Brayton in the 19th century, was the first successful gas engine built in the United States. The cycle is particularly suited to turbine machinery because of its ability to handle large volumes of gas more efficiently and has a secondary advantage in that it carries out its heat transfer processes at constant pressure which is the easiest method with steady flow machinery.

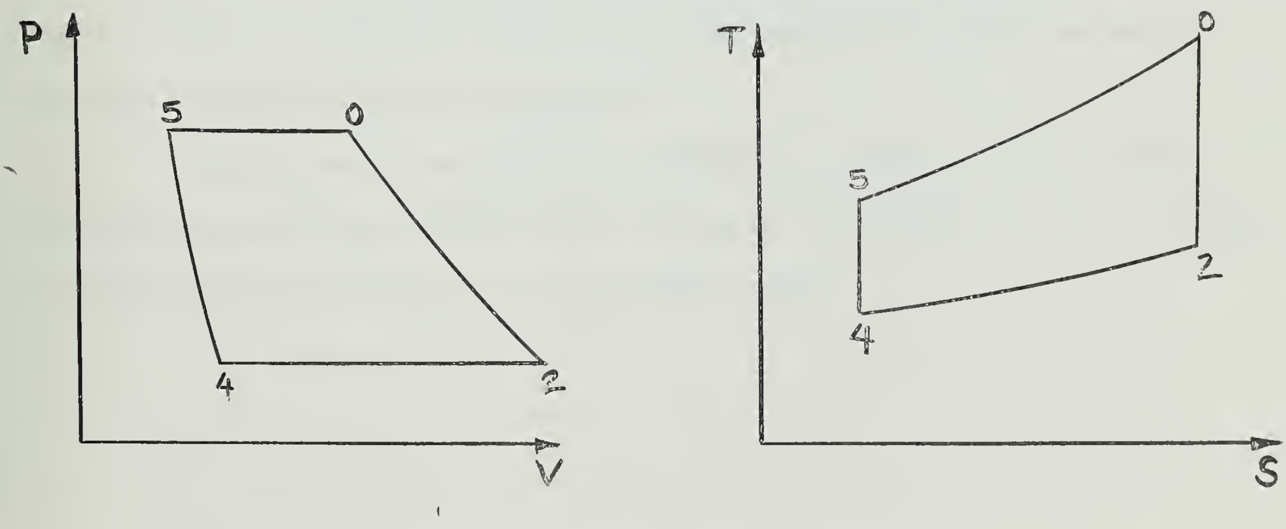

Figure III (Thermodynamic State Diagrams for the Ideal Brayton Cycle)

The efficiency of the ideal Brayton cycle is

$$\eta_{cyl} = \frac{\text{net work output}}{\text{net heat input}}$$

$$= \frac{Q_1 - Q_2}{Q_1}$$

$$= 1 - \frac{mCp\ (T_2 - T_4)}{mCp\ (T_0 - T_5)}$$

where m is the mass of the fluid, C_p is the specific heat at constant pressure, Q_1 and Q_2 are the heat supplied and withdrawn, T is the temperature at the indicated state, and $Q_1 - Q_2$ is the net work output from conservation of energy.[20]

Applying the Brayton cycle to the MHD system is shown by Figures IV and V, where the Brayton cycle is somewhat modified from its ideal state. Process 0-1 is the isentropic expansion of the high-temperature working fluid to the high velocity needed for the MHD generator. Process 1-2 is the non-adiabatic extraction of energy from the working fluid in the MHD generator. Process 2-3 is adiabatic diffusion to transform a large part of the remaining dynamic head to static pressure head. The diffuser avoids excessive frictional dissipation due to the high velocities obtained and minimizes the compressor pump work. Process 3-4 is the constant pressure cooling through a heat exchanger. Process 4-5 is an adiabatic compression, and process 5-0 is the constant-pressure heating to complete the cycle.

The following sections will establish a suitable working fluid, define more clearly and analyze each component, and finally tie them all together to determine the performance of the complete cycle.

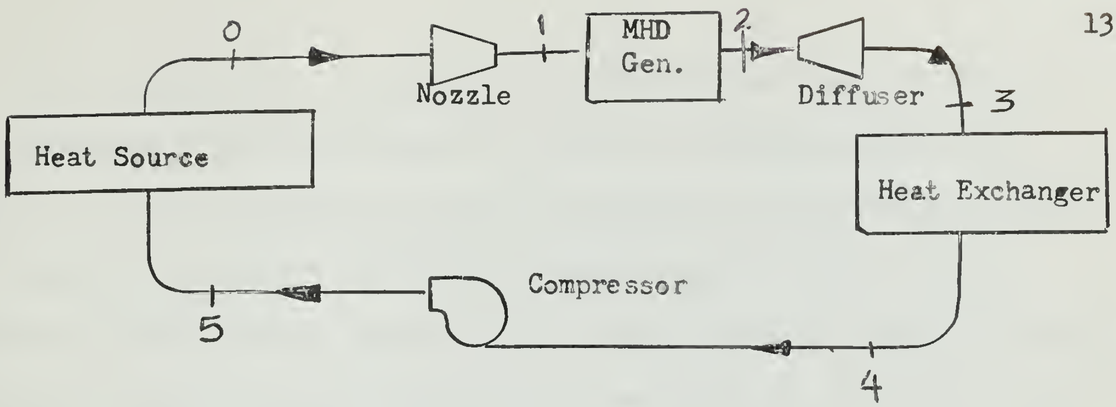

Figure IV (Schematic of Brayton Cycle MHD Power Generation System)

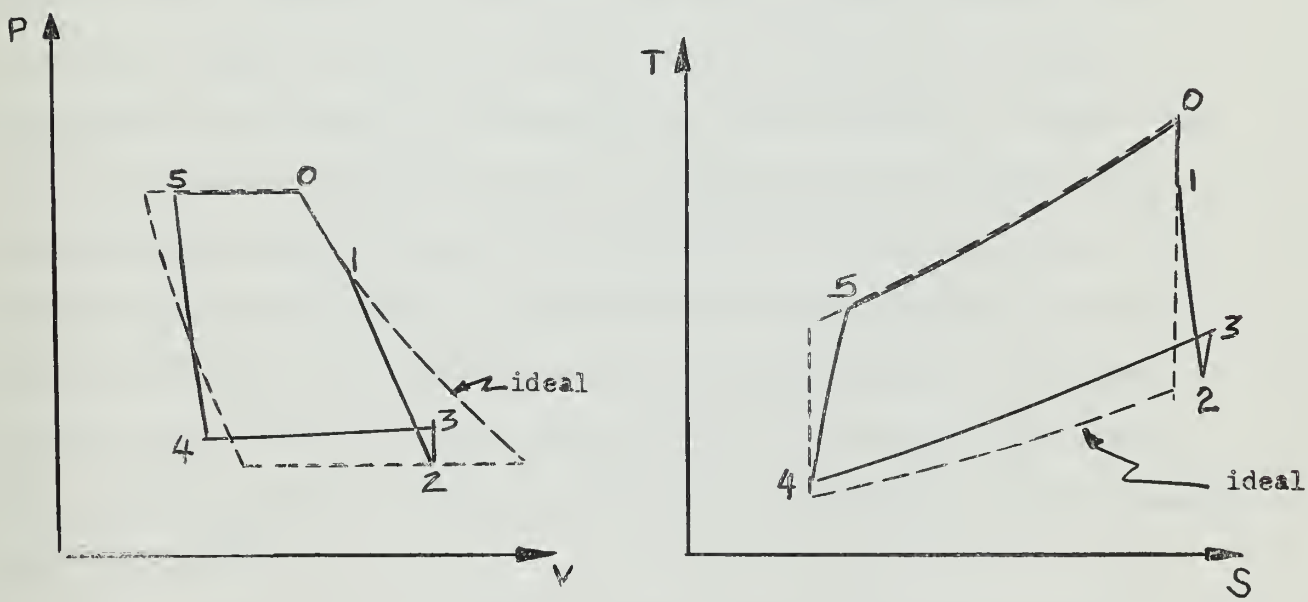

Figure V (Thermodynamic State Diagrams for the MHD Brayton Cycle)

2.2 Selection of the Working Fluid

Magnetohydrodynamic energy conversion relies on the fundamental basis that the fluid can be made to conduct electricity. To achieve this conductivity in a vapor MHD generator, it is necessary to ionize the gas by either of two types of ionization methods—"thermal" (or "equilibrium")

ionization accomplished by simply heating the gas, and "nonequilibrium" (or "extrathermal") ionization—both of which are strongly temperature dependent. Of the two methods, thermal ionization is unsatisfactory with the temperatures presently attainable from gas-cooled reactor plants (~1500°K).[9,20] This is because of the relatively high ionization energy associated with most gases and hence their inability to ionize until quite high temperatures are reached.[17] With nonequilibrium ionization, however, it may be possible to obtain the necessary electrical conductivity despite the relatively low temperature.[15,16,17,22] Nonequilibrium ionization, an already familiar process occurring in such devices as gas rectifiers and flourescent lights, is when the electrons within the gas are in thermal equilibrium at the electron temperature, but this temperature is higher than the equilibrium gas temperature due to an imposed electrical field. This action releases electrons from some fraction of the molecules, so that the positively charged molecules and the negatively charged electrons are then free to drift more readily through the gas under the influence of applied fields and give rise to a higher conductivity.[17] It should be mentioned here, however, that the stability of this type of ionization is still somewhat questionable.[17]

A great deal of work has been done, both theoretically and experimentally, concerning nonequilibrium ionization. In every case the most suitable fluids suggested were argon, helium, and neon, all seeded with a very small percentage (~1%) of either cesium or potassium. The cessium or potassium is added because it ionizes easily, giving a marked improvement in conductivity. Since conductivity increases with temperature and the imposed electric field and decreases with pressure, the selection of a working fluid from the above

three that best satisfies the requirements of thermal and electrical conductivity would most likely lead to the use of argon.[23] At this stage, however, the decision must be made whether an intermediate heat exchanger is to be used or whether the same fluid that is utilized by the MHD generator is also to be passed through the reactor to receive its heat. The two-loop cycle utilizing an intermediate heat exchanger will have higher heat losses than the single-loop cycle and is inherently more difficult to build, balance, and maintain. Since the single-loop system could more readily be placed within the reactor shielding because of the heat exchanger sizes, thus reducing nuclear and noise radiation, it apparently is the more advantageous of the two. If the single-loop system is used, then either seeded helium or neon should be used to minimize the fluid's deterioration under high radiation doses.[24]

Of the two, helium is the more popular nuclear coolant, having already been proven in several gas-cooled reactors.[22] The heat transfer considerations of specific heat and thermal conductivity favor helium almost five to one, and this is most important if concerned about volume restrictions. The electrical conductivity of neon, however, is slightly higher and holds up substantially better than helium with increased pressure.[23] But, since the cycle to be investigated will not be operated at extremely high pressures, the electrical conductivities of the two gases will not be significantly different and the more popular helium is therefore selected as the working fluid.

2.3 MHD Generator Considerations

Isolating the MHD generator for analysis reference will be made to Figure VI for the machine configuration and its associated coordinate system.

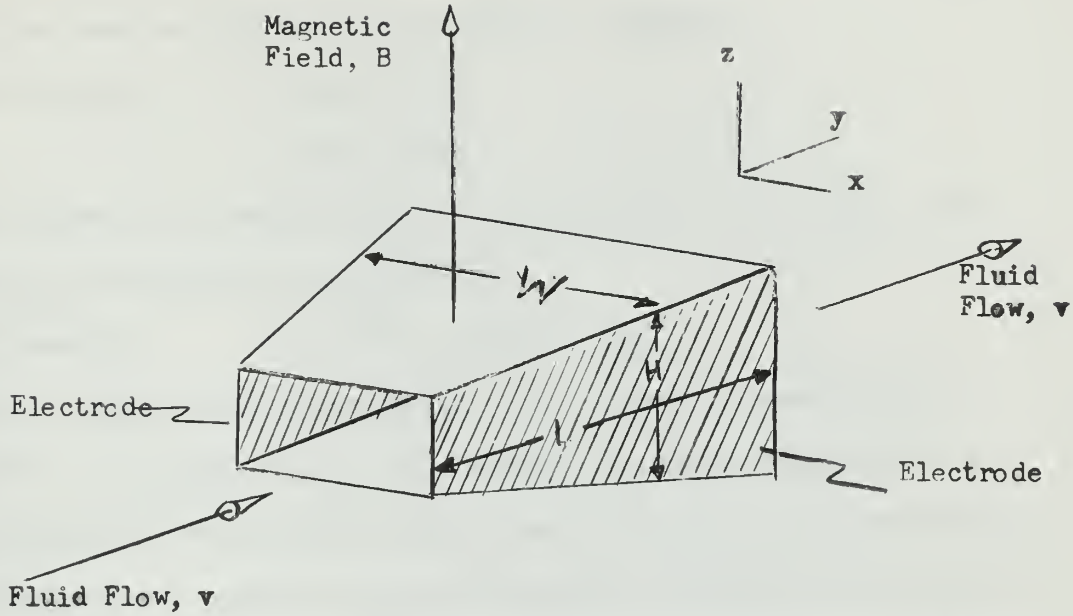

Figure VI (Schematic of MHD Channel)

The direction of fluid flow is in the y direction and is assumed to be independent of the x and z directions. The magnetic field is applied in the z direction and could be y-dependent. The electrodes are at the x = 0, and x = W walls, and the current is x-directed.

The basic mechanical equations of motion used in the solution for the one dimensional flow are:

Continuity: $$\frac{d}{dy}(\rho A v) = 0$$

Momentum: $$\rho v \frac{dv}{dy} = -\frac{dP}{dy} + (JB)$$

Energy: $$\rho v \left[Cp \frac{dT}{dy} + \frac{d}{dy}\left(\frac{v^2}{2}\right)\right] = JE$$

Equation of State: $$p = \rho g R T$$

Maxwell's equations, along with the constituent relationship for conduction current, completly describe the electromagnetic system. This results in the

remaining equations used to solve the basic MHD flow situation.

Current Density: $J = \sigma(E + vB)$

$= \sigma vB\,(1-K)$

where $K = -E/vB$ = generator loading factor, proportional to the average power consumed divided by the maximum power produced.

Power Density: $P_e = \overline{J}\,\overline{E} = -\sigma K(1-K)\,(vB)^2$

From this point, further assumptions must be made to complete the generator analysis. For instance, one could assume a constant temperature, a constant-current-density, and vary the velocity and the electrical conductivity. Likewise, and perhaps more realistic, one could assume a constant-velocity and analyze for a constant-current-density. Both of the above situations have been previously studied and the appropriate results are tabulated in Appendix I.[23] For the purposes of this paper, the constant-velocity, constant-current-density case is chosen for the forthcoming analysis.

Because the generator chosen for the cycle analysis used a constant-current-density, constant-velocity model, the conductivity became only a function of temperature and pressure as the fluid passed through the generator channel. McNary has shown that this variation has the form shown in Figure VII.[23] Since $B = J/(1-K)\sigma v$ = constant/σ, its typical curve is as depicted in figure VII.

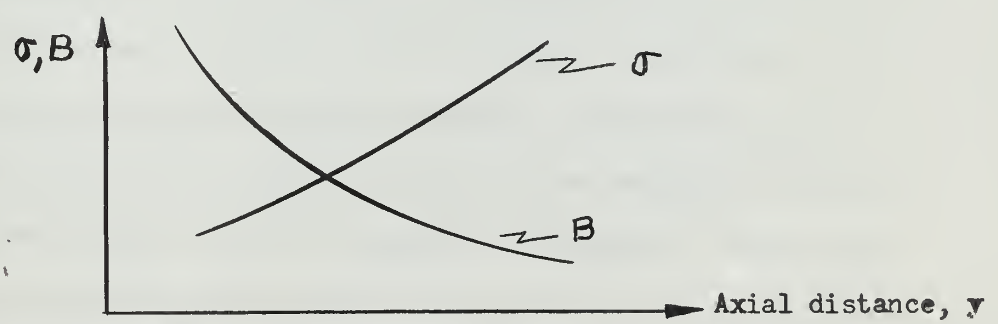

Figure VII (Typical Axial Variation of σ and B for the Constant-Velocity, Constant-Current-Density MHD Generator)

To operate the generator at the necessary high pressure levels consistent with the nuclear heat source, it is necessary to use high values of current density to obtain a suitable electrical conductivity. For the case at hand, if a current density of 10^5 amp/m^2 is used with a generator of length 1 meter, the required electrical conductivity ranges from 373 mhos/m at the entrance to the generator to 920 mhos/m at the exit when used with the necessary magnetic field having a strength of 44.7 to 18.1 kilogauss. This extremely high magnetic field required to produce the desired output power indicates the need for superconducting magnet field windings.

If one wanted to reduce the magnetic field requirements, an increase in velocity would appear to be the answer. However, as mentioned before, the thermodynamic cycle efficiency decreases with an increase in velocity and there would be less static enthalpy available in the fluid for transformation to electric power. It is also true that increasing velocity would increase the flow noise - an unwanted effect for a naval vessel.

2.4 Cycle Description and Analysis

From Figure IV, it is noted that the fluid leaves the heat source with the highest temperature of the system. A nominal outlet temperature of 1500°K (2700°R) is assumed from the nuclear reactor. From there, the fluid flows through the nozzle and the MHD generator, essentially one unit. The loading factor, K, is chosen as 0.85 to give reasonable efficiencies and a maximum output load of 11 megawatts is imposed. Since this power limit directly determines the size of the generator through the power density term, an analysis is first made to determine the power density

from which generator dimensions can be determined. To prevent abnormal degradation of the working fluid's electrical conductivity and because high working pressures are undesirable, a pressure of 10 atmospheres is used at the generator's inlet. From the generator, the diffuser converts the dynamic head to a static pressure head and reduces the fluid velocity to a negligible amount. A reasonable diffuser efficiency of 0.85 is used.

The heat exchanger is theoretically a constant-pressure device with salt water as the coolant. Since the water temperature restricts how low the cycle fluid can be cooled, an output temperature of 350°K (630°R) is assumed as a practical value.

The compressor will receive its power from the MHD generator output, and ideally is an adiabatic device. For cycle calculations a normal efficiency of 0.85 is again chosen for the compressor.

Another constraint on the cycle is that the temperature of the fluid through the generator remain high enough to provide for satisfactory electrical conductivity. It will be initially assumed that if the temperatures are above 800°K, the conductivity will remain satisfactory for efficient generator operation.

A high fluid velocity, necessary to produce a large induced electric field must be chosen. The value of 400m/s to be used in the analysis, although high from a noise standpoint, reasonably satisfies the generator requirements.

In summary, then, the following is a list of boundary conditions and assumptions utilized in conducting the Brayton cycle analysis:

Max Temperature (heat source)	1500°K
Generator loading factor, K	0.85
Velocity, maximum	400 m/s
Minimum temperature (gen.)	800°K
Power output	11 mw
Inlet generator pressure	10 atm
Diffuser efficiency	0.85
Diffuser outlet velocity	0.0
Heat exchanger outlet temperature	350°K
Compressor efficiency	0.85
Working fluid	Helium
C_p, He	534 m/°K
R, He	212 m/°K
γ, He ($\gamma = C_p/C_v$)	1.66

Utilizing these parameters and boundary conditions, thermodynamic cycle analyses were conducted, a sample of which is tabulated in Table I. The procedures used in calculating the thermodynamic properties are listed in Appendix II, and the states referred to are shown in Figures IV and V.

TABLE I - Thermodynamic Properties of Brayton Cycle Analysis

Thermodynamic State	Temp, T °K	Velocity, m/s	Entropy, s jl/kg°K	Pressure, p nt/m^2	Density, kg/m^3	Enthalpy, h jl/kg
0	1500	0	0	10.40×10^5	.333	78.4×10^5
1	1485	400	0	10.13×10^5	.328	77.6×10^5
2	942	400	422	2.64×10^5	.135	49.2×10^5
3	957	0	520	2.66×10^5	.134	50.0×10^5
4	350	0	-4730	2.66×10^5	.366	18.3×10^5
5	639	0	-4416	10.40×10^5	.783	33.3×10^5

The compressor work	$= h_5 - h_4 = 15.0 \times 10^5$ jl/kg
MHD generator total output	$= h_1 - h_2 = 28.4 \times 10^5$ jl/kg
Total output of cycle	= MHD output x gen. loading factor minus the compressor work
	$= 9.1 \times 10^5$ jl/kg
Total input	$= h_0 - h_5 = 45.1 \times 10^5$ jl/kg
Efficiency of cycle, η_{cyl}	= Output/Input = 20.2%

It should be noted that the energy required for the compressor is siphoned from the generator output, thus reducing the overall efficiency. For most applications, the compressor could feasibly be powered from the waste heat ejected by the heat exchanger through a secondary turbine cycle. Herein lies one basic difference between most land applications and this particular marine employment. To utilize a secondary cycle with a turbine on a ship would defeat one of the major reasons for investigating the MHD power cycle: noise reduction.

Although not apparent, increasing the velocity through the MHD generator decreases the efficiency. This is primarily due to the non-isentropic diffuser and compressor operating over temperature intervals which increase with increasing velocity. Hence, the increase in entropy is greater for these processes at higher velocities which leads to reduced cycle efficiencies. It is also true, from thermodynamic considerations alone, that decreasing the velocity below the sampled 400 m/s will increase the cycle efficiency, but the generator efficiency decreases with decreasing velocity as will be discussed in the following section.[23]

2.5 Results of the Brayton Cycle

Setting the output power requirement (11 mw) equal to the generator output, the remaining generator characteristics can be calculated. Table II gives a summary of the results obtained from one of the thermodynamic cycle analyses ($v \doteq 400$ m/s) where the generator's length was restricted to one meter. This restriction was due to anticipated volume limitations more than performance requirements as further investigation is needed to obtain an optimum dimension.

The 20% efficiency achieved in the investigation might tend to stimulate further interests in the Brayton cycle. It is, however, important to point out that many seemingly safe assumptions were made in order to conduct the analysis and the inclusion of these neglected items may well degrade the available output power resulting in totally unacceptable efficiencies.

Minor items neglected were such things as the I^2R losses in the working fluid and the visous losses due to the high fluid velocities. The major omission, however, was in failing to consider the power required to refrigerate the super conducting magnet. There are also other questions to be raised concerning the working fluid and its electric conductivity. Whether the fluid used (helium) can be rendered sufficiently conducting at the temperatures and pressures needed is not completely assured, and it is felt that more experiments in this area are needed before any further developments of this cycle are attempted.

An important consideration concerning the adaptation to a ship is the noise problem involved in such a large power plant. The cycle does successfully eliminate the large noise-producing turbines, but it is somewhat questionable, from a noise standpoint, whether the clamor caused by the required

Table II. Results of Brayton Cycle

a. Thermodynamic results

T_0	1500°K
T_4	350°K
T_1	1485°K
T_2	942°K
P_1	10 atm
P_2	2.6 atm
ρ_1	.328 kg/m^3
ρ_2	.135 kg/m^3
$h_1 - h_2$	28.4 x 10^5 jl/kg
η_{cyl}	20%
$v_{1,2}$	400 m/sec

b. MHD Generator results

J	10^5 amp/m^2
I	11,00 amps
V_t	1000 volts
L	1 m
σ	373---920 mho/m
B	44.7---18.1 kg
A_1	.0724 m^2
W_1	.66 m
H_1	.11 m
A_2	.1785 m^2
W_2	1.63 m
H_2	.11 m

velocity of 400 m/s through the MHD generator will be sufficiently less than the noise created by the steam turbine to warrant further investigations of this cycle.

Chapter III

ANALYSIS OF A RANKINE-CYCLE MHD POWER SYSTEM

3.1 General Description

Like the Brayton cycle, the ideal Rankine cycle consists of two reversible constant-pressure and two reversible adiabatic processes. The difference between the two is that the Rankine cycle operates through the liquid-mixture-vapor state of the working fluid rather than just the vapor portion. The diagram in Figure VIII depicts the thermodynamic states in a typical ideal Rankine cycle, corresponding to the cycle of Figure IX. The

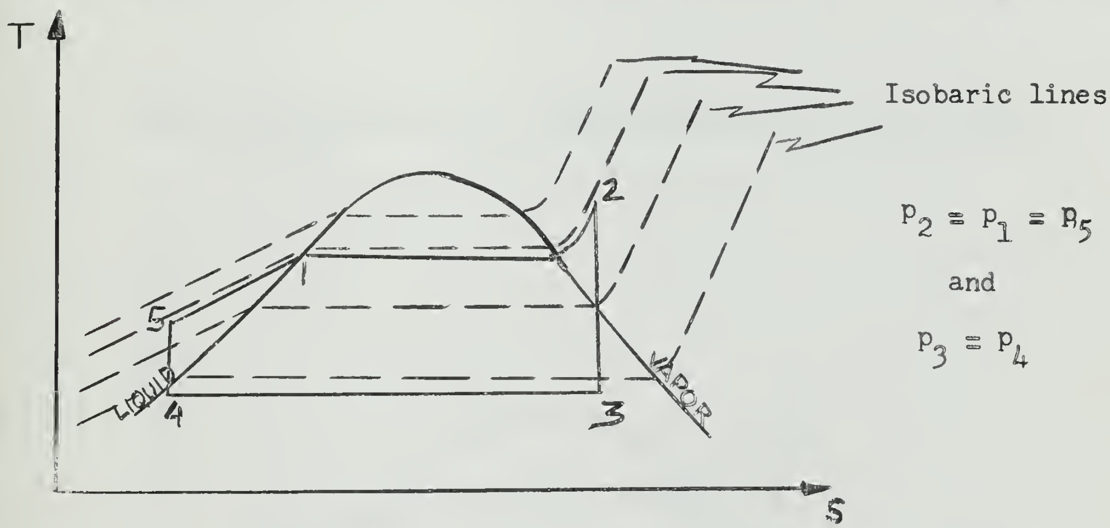

Figure VIII (Thermodynamic State Diagram for an Ideal Rankine Cycle)

ideal cycle efficiency is given by:

$$= \frac{\text{net work output}}{\text{heat input}}$$

$$= \frac{(h_2 - h_3) - (h_5 - h_4)}{(h_2 - h_5)}$$

$$= 1 - \frac{(h_3 - h_4)}{(h_2 - h_5)} \qquad (20)$$

where h is the enthalpy at the corresponding states.

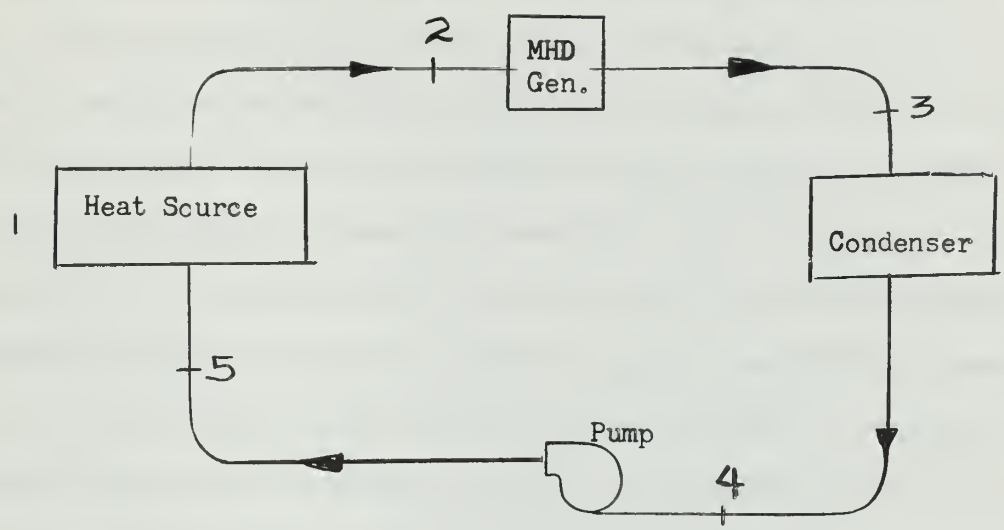

Figure IX (Schematic of a Typical MHD Rankine Power Cycle)

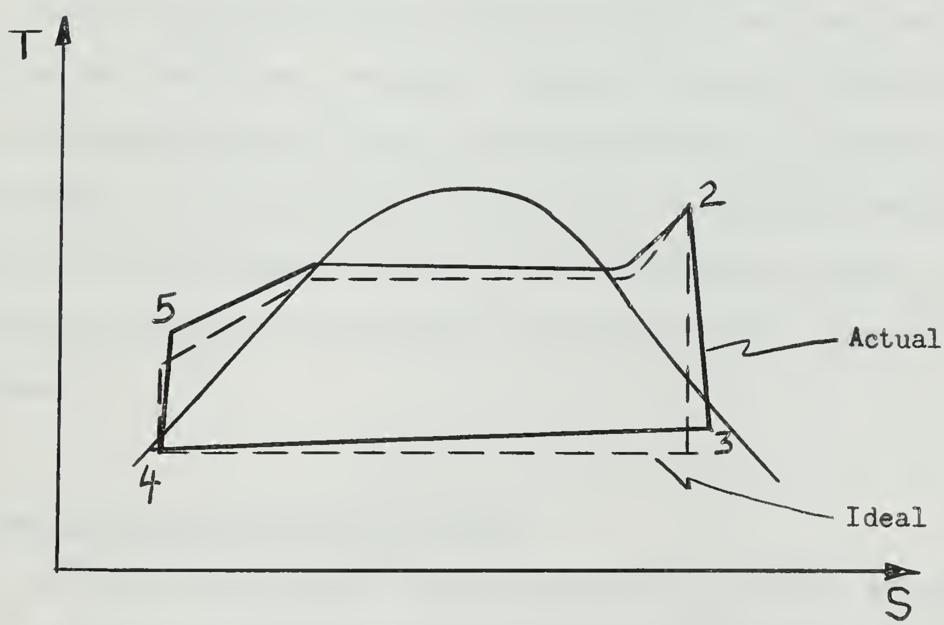

Figure X (Thermodynamic State Diagram for a Typical MHD Rankine Cycle)

Referring to Figures IX and X, a more realistic MHD system is illustrated. The liquid at point 4 is pumped to the pressure at point 5 which, ideally, would correspond to the saturation pressure at points 1 and 2. However, due to fluid friction and momentum changes, there is a slight pressure drop as the fluid is heated and vaporized in the heat source. The resulting vapor is then passed through the prime mover (i.e. the MHD generator), where it ideally undergoes isentropic expansion and the possibility of some condensation. In the actual cycle there is a slight increase in entropy. The downgraded fluid is then condensed to point 4 as it rejects heat.[25] The expansion process could also take place completely in the vapor state or completely within the partial condensation state.

3.2 Discussion of Possible Cycles and Their Working Fluids

Several basic liquid-metal MHD power cycles have been proposed, studied, and to some degree, developed. They all utilize a Rankine thermodynamic cycle to convert thermal energy into kinetic energy or stagnation head of a liquid, which is then transformed into electric energy by an MHD generator. Following is a brief discussion of each cycle and how they differ, not only in the components used, but in the manner in which the energy conversion is accomplished.

3.2.1 Two-Component, Two-Phase MHD Cycle

One such power cycle is the two-component, two-phase MHD cycle initially proposed and analyzed by Elliott,[26] depicted schematically in Figure XI. It is noteworthy that Elliott is the originator of liquid-metal MHD cycles of this type and that this cycle is the initial one of its kind.

The cycle utilizes two fluids and two loops. The fluid in the liquid loop, usually specified as lithium, has a much higher boiling point than the fluid in the vapor loop, typically cesium or potassium.

In the vapor loop, the fluid, after condensing is pumped (by an electromagnetic pump) to the mixer where it vaporizes on contact with the hot liquid. The two-phase flow then expands through the nozzle into the separator where the vapor is removed before the entrance to the MHD generator and returned to the condenser. A heat exchanger is used to cool the vapor while preheating the condensate to raise the cycle efficiency.

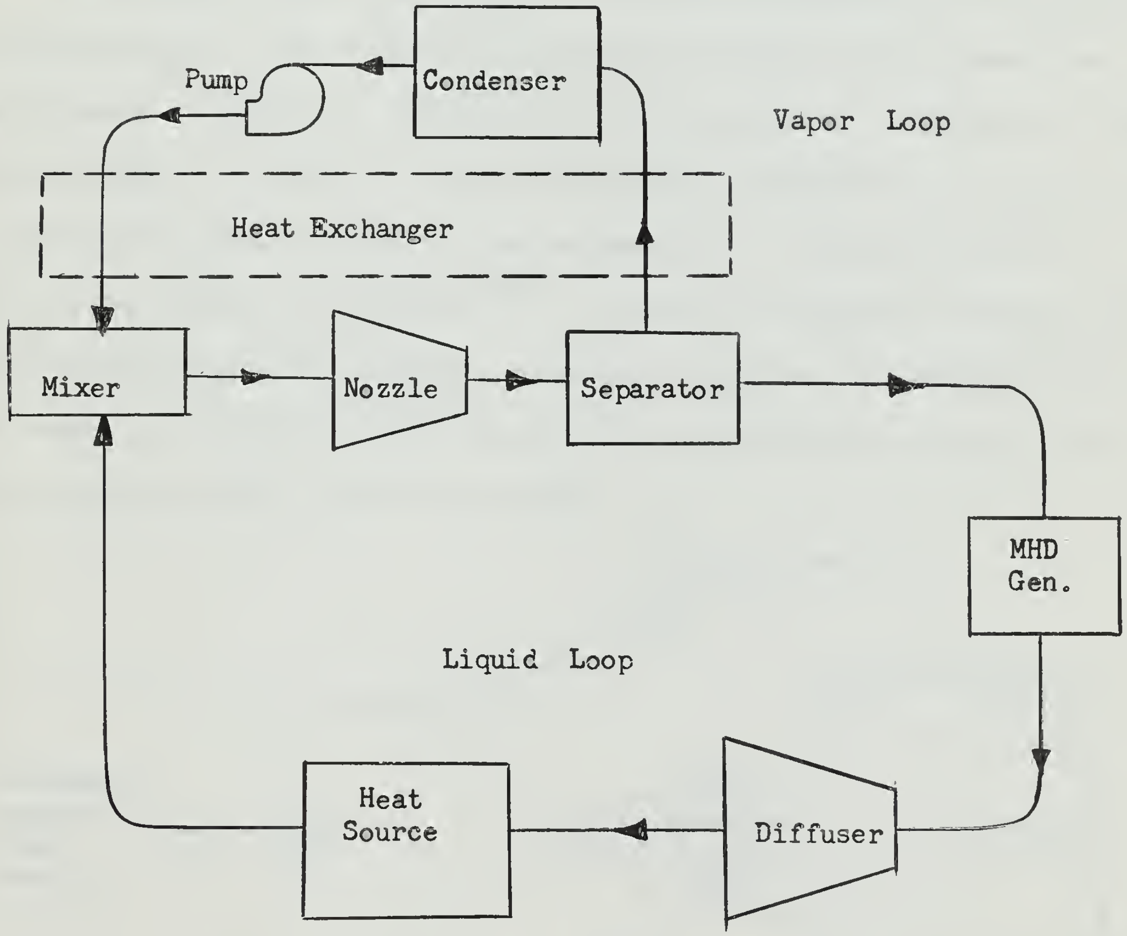

Figure XI (Schematic of Two-Component, Two-Phase MHD Cycle)

The liquid, or power, loop is where the high-boiling-point fluid is heated in the reactor and passed into the mixer where the liquid gives up heat as the condensate is vaporized. The two-phase flow is than accelerated by the atomized condensate through the nozzle until separated from the vapor. This separation occurs when the two-phase flow strikes a conical-like device as shown in Figure XII, capturing the liquid on its surface and allowing the vapor phase to continue through its segregated cycle. The liquid phase is then shunted through the separator's "liquid capturing" slot to the MHD generator where the flow is decelerated by the production of electric power. The liquid is then returned to the reactor via a diffuser.

The success of this cycle rests with the performances of the separator and the MHD generator. The separator is subject to large viscous losses and the completeness of separation appears to be an uncertainty. Since most of the analytical efforts involving this cycle have assumed idealized conditions, the effect of this incomplete separation on the generator's performance and the balancing of the system is not known.[26] It should be mentioned, though, that there has been much interest recently concerning two-phase flow MHD generators and the results of these studies[27] will aid in determining the cycle's performance regardless of the separation problem.

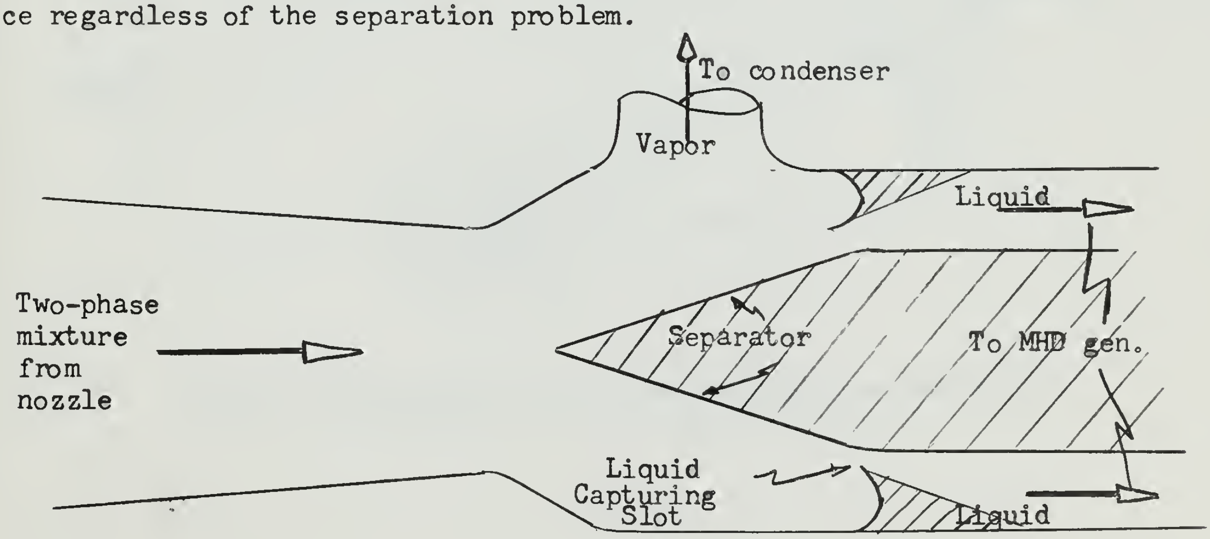

Figure XIII (Schematic of Separator Device)

3.2.2 Condensing-Ejector MHD Cycle

The condensing-ejector liquid-metal MHD power cycle originated by Jackson and Brown(28) is shown in Figure XIII. The cycle, strongly dependent on the performance of the condensing-ejector, consists of a liquid loop and a vapor loop, similar to Elliott's cycle. In this cycle, however, a single fluid is used in both loops, and it is the vapor which is generated in the reactor heat source and mixed with the liquid stream in the condensing-ejector. Cycle analyses have been performed with cesium, potassium, sodium, and mercury, with mercury and cesium showing the highest efficiencies.(15)

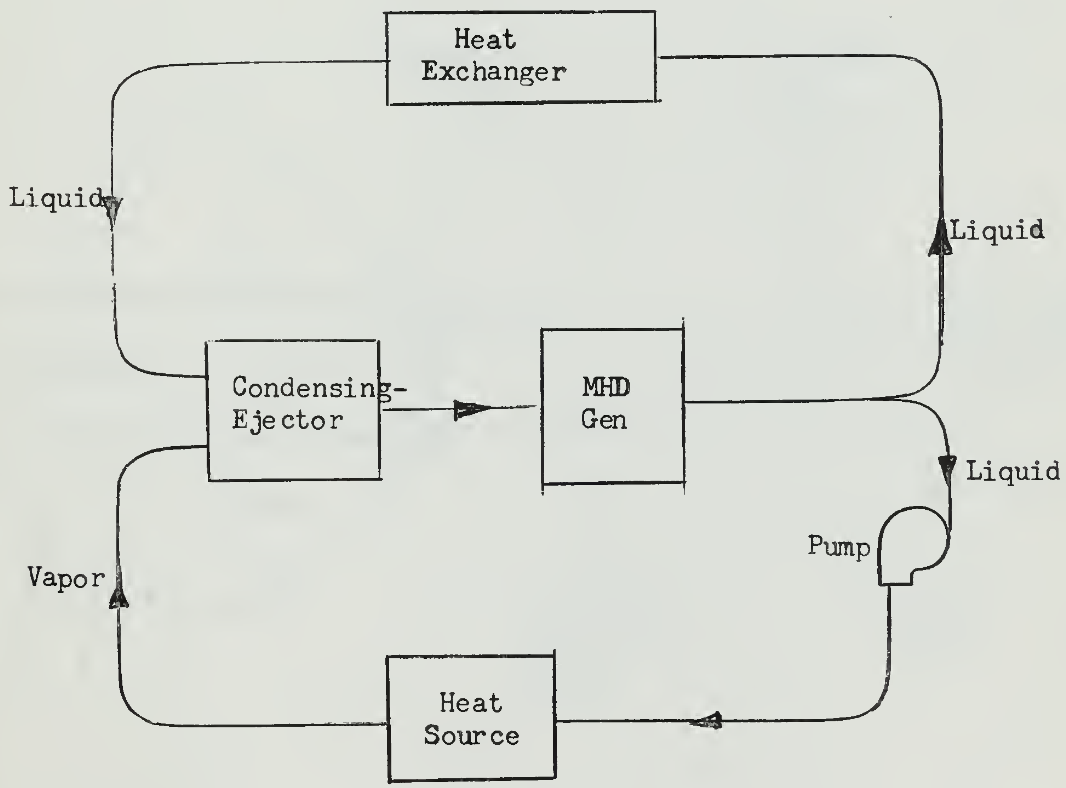

Figure XIII (Schematic of Condensing-Ejector MHD Cycle)

In the condensing-ejector (Figure XIV), both liquid and vapor are nozzled before entering the mixing section, and the condensation shock set up in the constant-area section should result in a purely liquid stream being obtained at the outlet. An additional advantage is that a higher stagnation pressure is often available at the outlet than either of the inlet points and this characteristic would probably allow for the elimination of the pump shown in Figure XIII.[29]

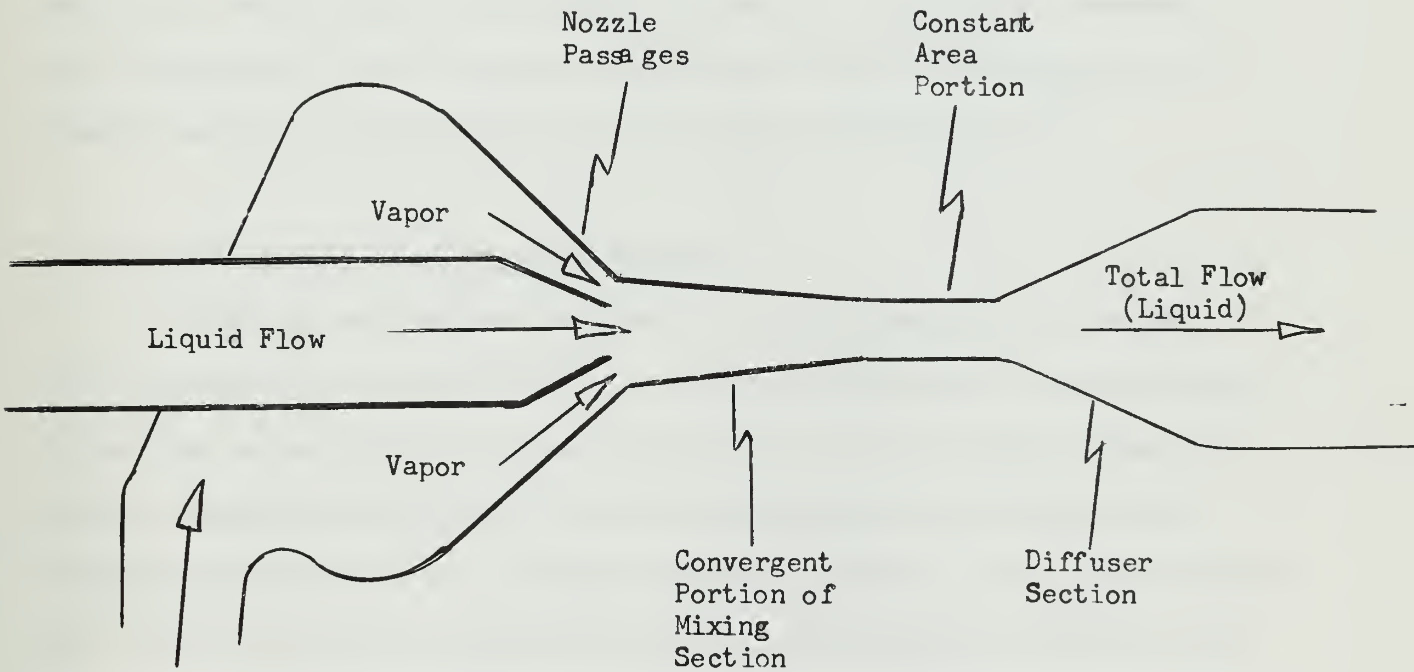

Figure XIV (Schematic of the Condensing-Ejector)

Thus, in the condensing-ejector, the vapor is condensed and a high-stagnation-head liquid is generated. The fluid then passes through the MHD generator where electrical energy is extracted at the expense of the stagnation pressure head. The fluid, still a liquid at this point, then divides into two streams, one of which passes into the vapor loop and the reactor, and the other to the liquid loop where heat is removed.

As in the Elliott cycle, a major advantage of this cycle is that a single-phase liquid-metal should pass through the generator, resulting in a very high electrical conductivity and power density. It is emphasized, however, that it is the condensing-ejector's performance which is the key to this cycle, and although the present efficiencies of this device somewhat limit the system, there is recent evidence that future investigations will greatly improve its operation and thus the cycle efficiencies.[30]

3.2.3 One-Component, Two-Phase MHD Cycle

Petrick and Lee have proposed the one-component, two-phase MHD cycle illustrated in Figure XV.[27] A two-phase mixture as a saturated vapor leaves the reactor heat source and increases its kinetic energy through the nozzle. The mixture then passes through the MHD generator (still in its two-phase state), where the electrical energy is removed, and into the condenser. The fluid is then condensed into the liquid state and returned to the reactor by means of a diffuser. In comparing with the previous two schemes, the condensing-ejector and the separator are noticeably missing, greatly simplifying the cycle and with the possibility of an increase in efficiency and less generated noise.

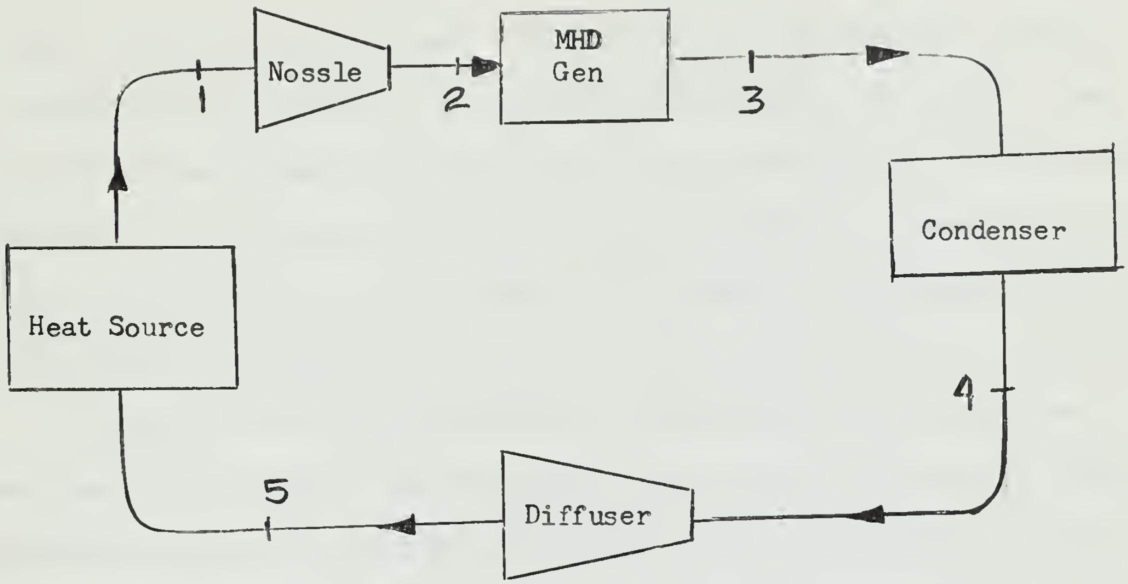

Figure XV (Schematic of One-Component, Two-Phase MHD Cycle)

Because the flow through the generator is two-phase, the performance of this cycle is strongly dependent upon the MHD generator. The effect of the vapor phase on the generator performance is under a great deal of study,[27] particularly since conductivity data on two-phase mixtures is not available. Petrick and Lee have suggested that two different types of generators be investigated for this cycle.[15] One is simply a variable-area generator which is expected to operate in a cycle where the fluid flow through the generator has a very low quality.* The other type of generator proposed is designed to operate when the fluid flow through the generator has a higher quality. It also has a variable area but is called a "film-flow" generator. This generator receives a high velocity flow at a small angle (~10°) to the generator bottom, where the liquid is separated from the vapor by impingement

* Quality is defined as the fraction, by mass, of vapor in the mixture. Thus, if the quality, X, is equal to 1.0, the "mixture" is entirely vapor.

and a high velocity film is formed. Interacting with the magnetic field, the film builds up in thickness as the electrical energy is extracted. The possibility of condensing the vapor phase on the rapidly moving film by cooling the underside of the generator is also under investigation. The efficiency of this type of generator will be a function of the degree of separation and the film interactions[15] but may be limited by high viscous losses.

Previous studies on analyzing the efficiency of this cycle used mercury, potassium-mercury alloy, and three alkali metals—potassium, cesium, and sodium—as the working fluids, and these studies indicated that mercury gave the highest efficiency with potassium yielding the best efficiency of the three alkali metals considered.

3.2.4 Concluding Remarks on the Three Proposed Cycles

Because all three cycles are still under intensive experimentation and investigation, it is felt that an analysis of any one will essentially answer the question this portion of the thesis proposes: i.e. whether an MHD Rankine cycle can be utilized as a marine power source for nuclear-powered vessels. Thus, somewhat arbitrarily, the third cycle discussed (Petrick's) will be treated in the following sections. Again, it is emphasized that it is not felt that this cycle is better than the others but is being analyzed as an example of an MHD Rankine cycle. All three cycles require further theoretical and experimental investigations before accurate predictions of both performance and noise level will be possible.

3.3 One-Component, Two-Phase MHD Cycle Analysis

The proposed cycle is schematically illustrated in Figure XV. Consisting of five basic components, the cycle utilizes a two-phase mixture or a

saturated vapor from the reactor through a nozzle where its kinetic energy is increased for the extraction of electric energy in the MHD generator. The fluid then passes through a condenser and returns to the reactor via a diffuser.

In analyzing the cycle, each component will be briefly described and discussed. The cycle efficiency is determined from the thermodynamic diagram in Figure XVI where the numbered states refer to the positions shown in Figure XV.

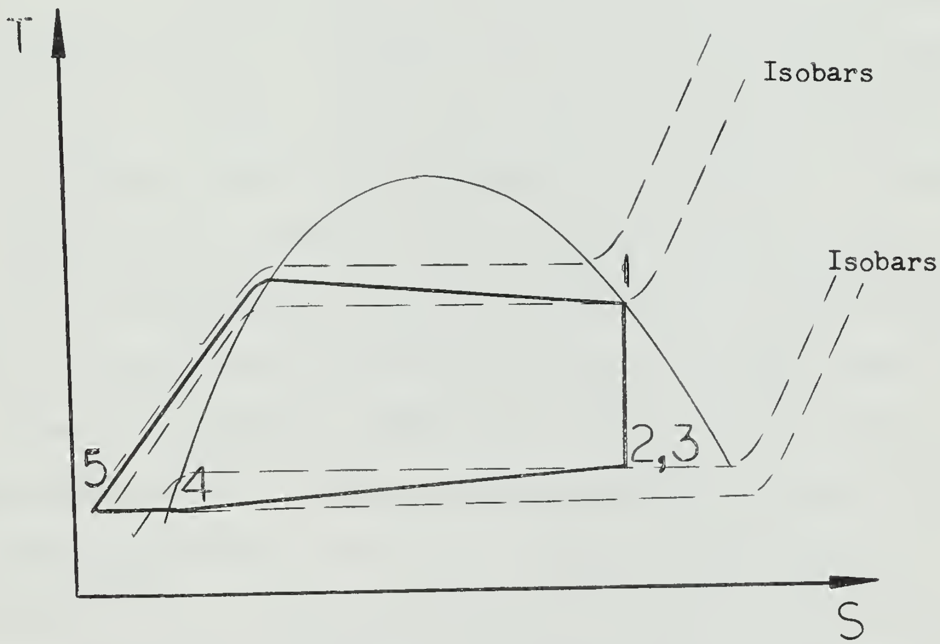

Figure XVI (Thermodynamic State Diagram for the One-Component, Two-Phase MHD Cycle)

The two-phase nozzle is assumed to be almost isentropic with a nozzle efficiency of 0.90 (i.e. the exit velocity squared is taken as equal to 90% of the ideal, or lossless, exit velocity squared). To satisfy the flow conditions, the nozzle size would have an exit area on the order of 0.05 m^2 and a correspondingly larger entrance area on the order of 0.2 - 0.3 m^2. The flow would be fully in the subsonic range.

The generator used in this cycle is a variable-area, film-flow type developed by Petrick and Lee to increase the cycle efficiency with a two-phase flow through the MHD generator.[15] This generator, still in an early stage of development, receives the high-velocity fluid from the nozzle at a small angle ($\sim 10°$) to the lower surface of the generator's channel. The liquid is then separated from the vapor by impingement and a high-velocity film is formed. The film, interacting with the magnetic field as electrical energy is extracted, builds up in thickness, thereby enhancing the generator's performance. It is also possible to cool the bottom side of the generator which has the possibility of producing some condensation and increasing the liquid flow in the generator. This is also currently under study.[15] Until studies are finalized, then, hearty assumptions are necessary to complete a cycle analysis for this system. Thus, to greatly simplify matters, it will be assumed that the generator is a constant-temperature, constant-quality device with an output proportional only to the kinetic energy change through its flow channel. The generator efficiency, defined in this cycle as the ratio between the actual exit flow velocity squared to the ideal exit flow velocity squared, is assumed to be 0.75, conforming to the analysis of Petrick and Lee.[13] The ideal exit velocity is taken as that velocity which would exist without the effect of friction and viscous losses.

The condenser operates at the lowest temperature of the cycle and has tapered channels to maintain a constant velocity. This velocity is required to prevent the working fluid from cooling too rapidly and extending too far into the liquid state before re-entering the reactor for heating. It is assumed that the condenser has a 10 psi (6.9×10^4 nt/m^2) pressure drop as the fluid passes through it. This figure is chosen to account for fluid friction and momentum changes.

The diffuser is assumed to be an adiabatic device which essentially reduces the remaining kinetic energy to a negligible amount before it enters the heat source. A nominal diffuser efficiency of 0.9 will be used for purposes of analyzing the cycle.

The heat source, or reactor, is assumed to have a small pressure drop of 10 psi due to fluid friction and changes in momentum caused by phase changes. It is further assumed that the reactor heats the fluid to a maximum of 1500°K (2700°R).

Previous analyses of this system demonstrated a variation with the mixture quality, X, and cycle efficiency, as shown in Figure XVII. As illustrated, the highest efficiencies were obtained with a mixture quality of 1.0 (pure vapor) at the entrance to the nozzle. This maximization is due to the increased kinetic energy available as the higher quality mixtures enter the MHD generator,[15,31] which compensates somewhat for the expected poorer performance due to higher mixture qualities in the generator.

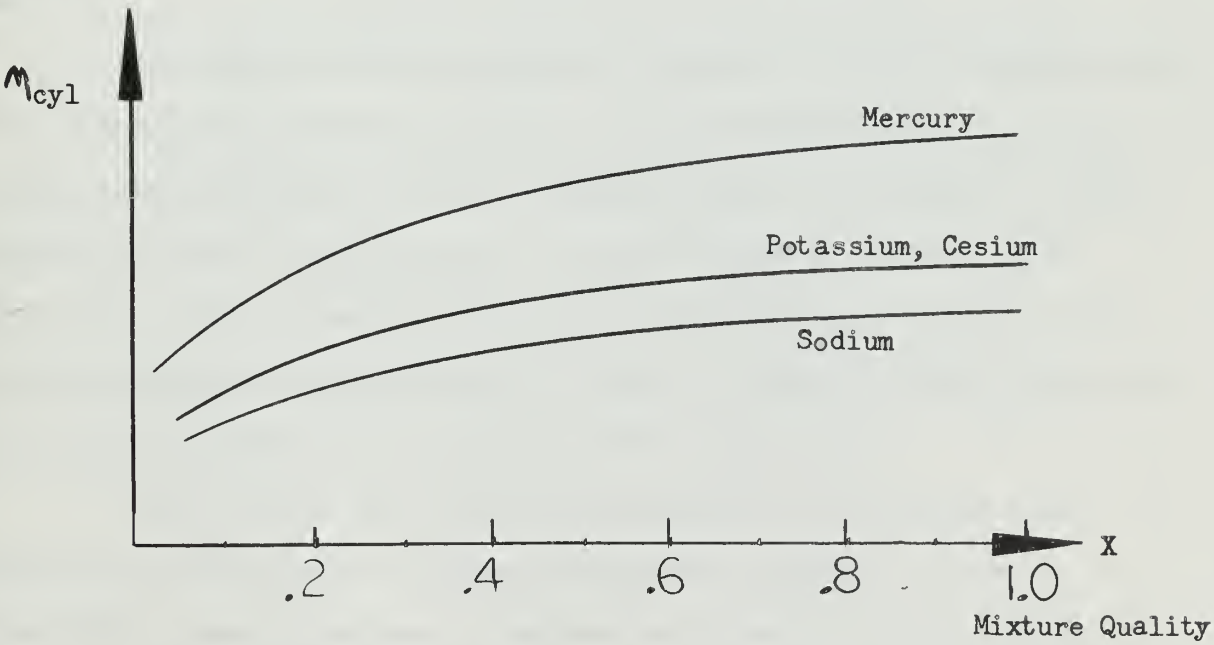

Figure XVII (Typical Variation of Cycle Efficiency and Mixture Quality for Different Working Fluids for the One-Component, Two-Phase MHD Cycle)

These same previous analyses studied the aforementioned working fluids (also in Figure XVII) and indicated that pure mercury gave the highest efficiencies because of the high kinetic energy conversion from enthalpy per pound mass of working fluid. The vapor pressure of mercury, however, rises rapidly with temperature, and one is forced into a high-pressure, high-temperature system. Potassium does not have this problem, but the theoretical efficiencies obtained were somewhat lower than for pure mercury.

Thus, for the following study, a nozzle entrance mixture quality of 1.0 will be assumed, and both mercury and potassium will be considered. It is cautioned, however, that using a high-quality mixture greatly reduces the electrical conductivity of the working dluid, so that the high value used ($X = 1.0$) used in this analysis may not be realistic as far as the generator's performance is concerned. Since this study is mainly for illustrative reasons it is felt that the particular value of X assumed is somewhat immaterial. It will affect the numerical results, but not the general conclusions.

The thermodynamic and physical properties of mercury and potassium were extracted from references(24, 32, and 33). Because of the high vapor pressures associated with mercury, a maximum reactor temperature of 1220°K (2200°R) was used, corresponding to a vapor pressure of 20×10^6 nt/m^2 (3000 psia). Since potassium doesn't have such high vapor pressures, the maximum available temperature from the reactor of 1500°K (2700°R) was chosen for the cycle analysis with potassium as the working fluid.

The effect on cycle efficiency obtained by varying the sink temperature while holding the source temperature constant is shown in Figure XVIII, where a maximum is observed for mercury with a sink temperature of 560°K (1000°R) and for potassium with a sink temperature of

780°K (1400°R). These characteristics are due solely to the thermodynamic properties of the fluids.

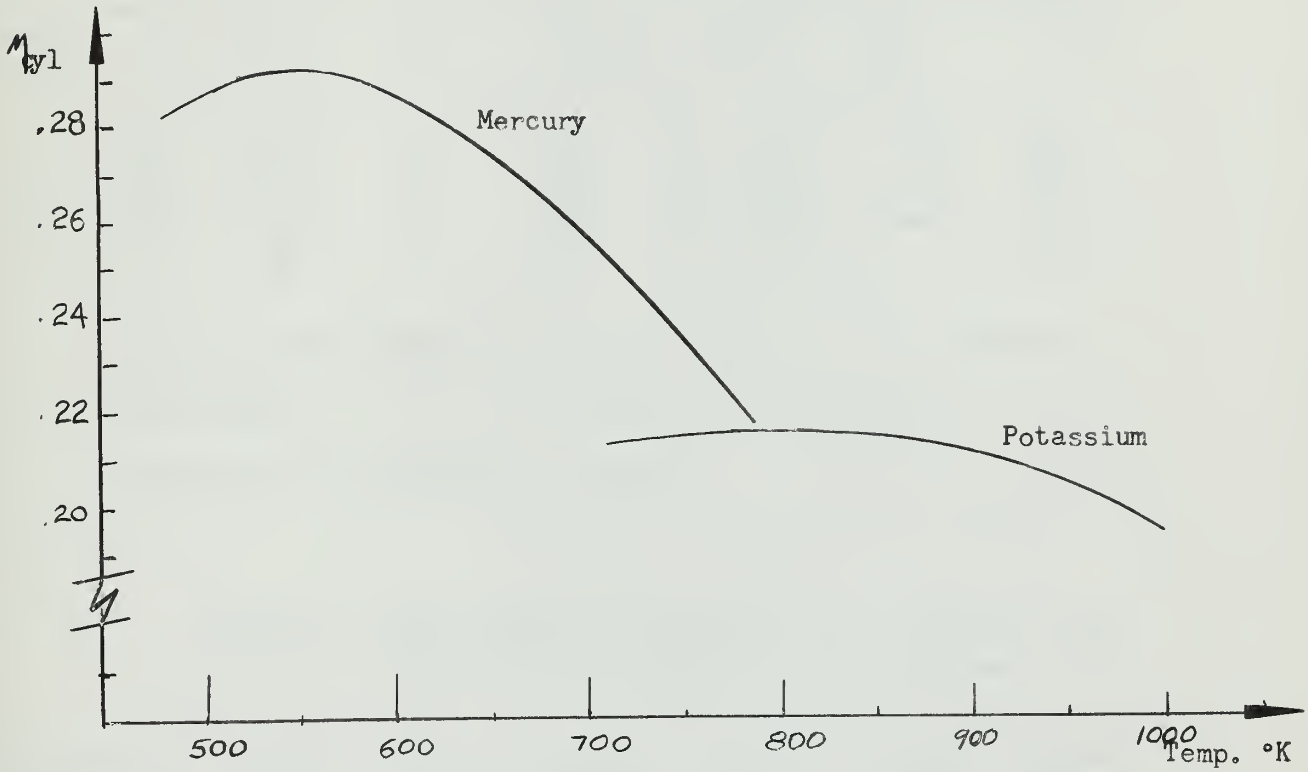

Figure XVIII (Effect of Condenser Temperature on Cycle Efficiency for the One-Component, Two-Phase MHD Cycle)

Using the previously discussed assumptions, thermodynamic cycle studies were conducted using mercury and potassium respectively as the working fluids. The procedures used in calculating the thermodynamic properties are listed in Appendix III, and the states referred to are shown in Figures XV and XVI. Samples from the cycle analyses are tabulated in Tables III and IV.

Table III. Thermodynamic Properties of One-Component, Two-Phase MHD Cycle Analysis with Mercury

Thermo State	Quality X	Temp, T °K	Velocity m/s	Entropy BTU/kg°K	Pressure, p nt/m^2	Density kg/m^3	Enthalpy, h BTU/kg
1	1.00	1220	0	.158	2.1×10^7	411.0	91.0
2	0.69	620	540	.158	9.1×10^4	4.9	59.0
3	0.69	620	60	.158	9.1×10^4	4.9	59.0
4	0.00	560	60	.094	2.2×10^4	13300.0	17.7
5	- -	560	0	- -	2.11×10^7	- -	17.7

MHD generator output $= \eta_g(v_2^2 - v_3^2)/2g = 21.4$ BTU/kg

Heat input $= h_1 - h_5 = 73.3$ BTU/kg

Efficiency of cycle, $\eta_{cyl} = 29.2\%$

Table IV. Thermodynamic Properties of One-Component, Two-Phase MHD Cycle Analysis with Potassium

Thermo State	Quality X	Temp, T °K	Velocity m/s	Entropy BTU/kg°K	Pressure, p nt/m^2	Density kg/m^3	Enthalpy BTU/kg
1	1.00	1500	0	.83	1.87×10^6	6.62	576
2	0.75	995	1100	.83	7.3×10^4	0.48	445
3	0.75	995	78	.83	7.3×10^4	0.48	445
4	0.00	780	78	.50	4.14×10^3	720.00	152
5	- -	780	0	- -	1.94×10^6		152

MHD generator output $= \eta_g(v_2^2 - v_3^2)/2g = 93$ BTU/kg

Heat input $= h_1 - h_5 = 424$ BTU/kg

Efficiency of cycle, $\eta_{cyl} = 21.9\%$

3.4 Results of the Rankine Cycle

Since the fluid flow through the MHD generator is assumed to have constant thermodynamic properties, the electrical conductivity is not expected to change. However, the velocity change, producing the generator output is considerable, and as a result, the current density change over the length is considerable. For the two fluids analyzed, the power requirement (11 mw) was equated to the available generator output to obtain the generator characteristics. A nominal length of 1 meter was chosen along with a conductivity based on the liquid's electric conductivity and the void volume fraction (estimated) within the generator channel as indicated in Appendix IV. Table V gives a comparative summary of the results obtained employing mercury and potassium as the working fluids.

Both of the theoretical cycle efficiencies compare favorably with existing turbo-electric systems. What is an immediately noticeable difference, however, is the abnormally low terminal voltages obtained. These voltages can be increased somewhat by going to high-aspect-ratio channels, but the obvious modification is to alter the type of generator from D-C to the A-C induction type previously introduced. The induction generator will eliminate the low voltage problem and could easily supply the power required for both propulsive and service purposes. The induction generator, which could be operated on liquid-metal flows, will be discussed in more detail in the next section.

In comparing the mercury and the potassium results, the efficiency of the mercury cycle is higher, but so is the peak operating pressure. Thus, it must be decided whether efficiency can be sacrificed for a lower, safer pressure, and this will depend on the application. On a ship, for instance,

Table V. Results of Rankine Cycle

Mercury - Working Fluid		Potassium - Working Fluid	
T_1	1220°K	T_1	1500°K
T_4	560°K	T_4	780°K
$T_{2,3}$	620°K	$T_{2,3}$	995°K
p_1	207 atm	p_1	18.5 atm
$p_{2,3}$	.9 atm	$p_{2,3}$	.72 atm
$X_{2,3}$	.69	$X_{2,3}$	.75
MHD_{out}	21.4 BTU/kg	MHD_{out}	93 BTU/kg
η_{cyl}	29%	η_{cyl}	22%
$v_{2,3}$	540 - 60 m/s	$v_{2,3}$	1100 - 80 m/s
J	$3.7 - .4 \times 10^6$ amp/m^2	J	$5.4 - .4 \times 10^6$ amp/m^2
I	3.4×10^5 amp	I	8.4×10^5 amp
V_t	32 volts	V_t	13 volts
L	1 m	L	1 m
σ	1.7×10^5	σ	3.3×10^5
B	3 kgauss	B	1 kgauss
A_2	.037 m^2	A_2	.041 m^2
W_2	.221 m	W_2	.140 m
H_2	.168 m	H_2	.290 m
A_3	.336 m^2	A_3	.580 m^2
W_3	2.0 m	W_3	2.0 m
H_3	.168 m	H_3	.290 m

the high pressures would be most undesirable, and the potassium cycle would prevail as the better of the two.

As has been mentioned previously, the cycle performance strongly depends on the performance of the MHD generator operating with a two-phase fluid. It is feared, though, that the very liberal approximations made concerning the generator in order to complete the thermodynamic cycle analysis will be in error when the forthcoming experiments on the two-phase flow generator are analyzed.[34] For instance, the analysis in this paper was done with the mixture quality equal to 1.0 at the entrance to the nozzle giving qualities on the order of 0.7 through the generator. If a quality of 0.5 at the entrance to the nozzle is used, a quality of approximately 0.2 would result in the generator increasing the fluid's electrical conductivity but decreasing the overall cycle efficiency as shown in Figure XVII.

A known characteristic of the two-phase flow is that the gas phase will move much more rapidly than the liquid phase, and it was because of this that Petrick and Lee introduced the film-flow generator previously described. Since little is known about the electrical conductivities of two-phase flows, experimental results are sorely needed. For instance, the electrical conductivity for the two-phase flow is believed to be a function of the void volume fraction of the fluid.[27] This void fraction, in turn, is related to the mixture quality and the volume rate.[35] As a result, the conductivities used for the two fluids studied turned out to be considerably less than the liquid-metal's conductivity (at the same temperature) and was reflected in the generator's characteristics (i.e. to obtain the necessary power, larger dimensions and magnetic fields were used than would be

necessary at higher electrical conductivities and, hence, higher power densities).

Despite these "engineering approximations," however, it is felt that future experimental evidence on the generator, the two-phase flow, and the overall cycle performance will further extablish it as worthy of more extensive investigation. It is interesting at this point to return briefly to the cycles proposed by Elliott, and by Jackson and Brown, and note that these cycles were not troubled with two-phase flow generators and that their overall complications may not turn out to be as serious as the problems in the cycle proposed by Petrick and Lee. This thesis, however, was not intended, at this early stage of development, to establish which of the cycles will perform the best, but rather to use one of them in an attempt to show that an MHD Rankine power cycle has the possibility of eventually replacing the steam-turbo drives on marine vessels.

3.5 D-C and A-C MHD Generators

As shown by the previous analysis, terminal voltages for the D-C MHD generator are expected to be abnormally low for the liquid-metal cycles, leading to high currents. Because of this, and because the direct generation of A-C power would be very useful, it seems worthwhile to briefly cover some of the possibilities of A-C generation in the hope of solving the low voltage problem and simultaneously producing serviceable A-C power without the use of inversion equipment.

From the terminal voltage relation ($V_t = KWvB$), one possible method of A-C generation is to alternate the magnetic field. This type of conduction machine, however, would still have very low terminal voltages, and probable

large magnet winding losses as A-C superconducting magnets are not feasible.[9,19,36] Pierson and Jackson[14] have proposed an MHD induction generator for liquid-metal flows, which could produce any desired voltage and eliminate the need for electrodes. This generator, shown schematically if Figure XIX, is the MHD analog of a conventional rotating induction generator, and its fluid velocity, v, must exceed the phase velocity, v_s, of the traveling magnetic field (produced by the polyphase windings of Figure XIX) in order to produce power. Preliminary studies[37] of this type of machine indicate that a reasonable performance level is attainable.

Inherent with induction machines is the associated reactive power, so that large capacitors must be introduced into the electrical system to supply this reactive power. Because of the difference in energy densities between inductances and dielectrics, the total capacitance volume would be approximately fifteen times the volume of the generator's channel for the cycle analyzed in this paper. A second consequence is that there might be appreciable losses in the electric circuit due to the circulating reactive power, which could be somewhat reduced by using mica capacitors.[19] The apparent advantages gained from

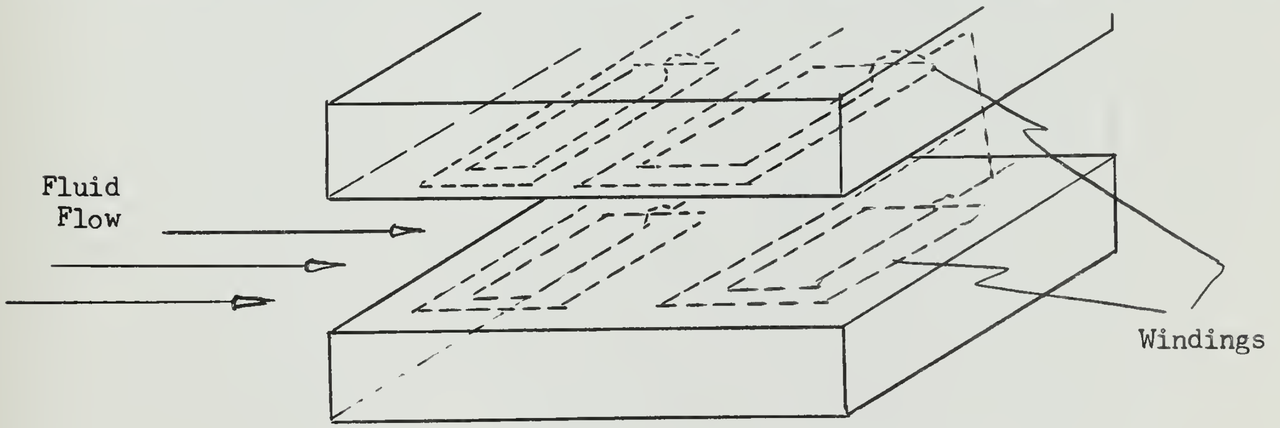

Figure XIX (Schematic of Linear MHD Induction Generator)

such a power source, however, far outweigh the minor nuisance of providing the capacitors. It is worth noting that if gases are used in lieu of liquid-metals in an MHD induction generator, the reactive power required is one to four orders of magnitude greater than the generator output power, resulting in a very inefficient operation.

In short, the possibility of A-C generation from an MHD induction generator appears feasible with liquid-metal flows. The generator could be wound for usavle voltages and could produce alternating power at suitable frequencies (60 cps) at reasonable efficiencies. The problem still remains for the induction generator, as well as for the D-C conduction generator, of including the effects of all the loss mechanisms and simultaneously matching the generator to the thermodynamic cycle.

Chapter IV

USEFULNESS AS A MARINE POWER SOURCE

Since the primary motivation for this study is an attempt to better the existing nuclear power plants on board ships, it is worthwhile to examine both types of MHD power cycles (Brayton and Rankine) in this regard.

Because the steam turbine systems on ships are inherently noisy, it was initially hoped that the MHD conversion scheme would practically eliminate this nuisance. In the steam systems, most of the noise is dereived from the high-speed turbine bearings, the associated reduction gearing, and the steam-turbine blade interactions. The MHD scheme utilizing slow speed propulsion motors, would eliminate these noise sources. The noise associated with such a system would therefore be due almost entirely to the flow of the working fluid. In the Brayton cycle, a minimum vapor velocity of 400 m/s (1300 ft/s) was used to generate the required power which is expected to produce some noise but not nearly as much as the present steam-turbine plants manufacture. Of the three Rankine cycles described, the two-component, two-phase cycle required a friction surface in the separator which is expected to be noisier than the Brayton cycle, but much less than the turbine system. The condensing-ejector cycle would likewise produce more noise than the Brayton cycle but still is expected to be quieter than the present shipboard systems. And, finally, the one-component, two-phase cycle would also appear to be much less noisy than the current turbine systems but would most likely be noisier than the Brayton cycle because of the high velocity (300m/s) two-phase flow.

Both cycles stress the no-moving-parts concept. Both must also contain materials which will withstand the high temperatures, pressures, and fluid reactions associated with either a gas-cooled or a liquid-metal-cooled reactor, especially since higher temperature systems are now under consideration. Basically, the areas which would cause the most trouble appear to be in the liquid-metal chemistry and the compatibility of the materials. Extensive programs, sponsored by the U. S. Atomic Energy Commission are now under way concerning these problems.

The theoretical efficiencies obtained are relatively equivalent to one another and most certainly competitive with current turbo-electric systems. Furthermore, future effective developments of the steam cycle seem unlikely, while the MHD cycle is just beginning to open up new avenues for investigation. In this respect, there is currently no strong reason to believe that the future MHD systems will not far surpass the present steam turbine systems in efficiency (and also in reduced noise levels).

The size and weight of the MHD plant does not appear to be a limiting factor. The spatial dimensions of the liquid-metal system are slightly more compact than the gas system due to the higher energy density and possibly a smaller magnet. Both systems would appear to be smaller (and lighter) than the current steam system. A problem could be presented, however, in the MHD scheme by the size of the required propulsion motor. Electric motors (A-C and D-C) developing 15,000 horsepower are of considerable size and weight and may not be adaptable to certain types of naval vessels.[12]

In the Brayton cycle, the terminal voltage and current could be adapted to a D-C motor, but there is no A-C power directly available from the generator itself. Thus, for shipboard use, the A-C required for normal ship-

board functions would come from inversion equipment (i.e. semiconductor inverters). In the liquid-metal Rankine cycle, the low D-C terminal voltage would require the use of very large current busses. A-C power, however, is theoretically available directly from the MHD induction generator, and could readily be adapted to propulsion induction motors as well as siphoned for service use. An alternative arrangement could utilize a D-C MHD generator for propulsion and an induction MHD generator for the other ship requirements.

In conclusion the MHD system is, in all likelihood, quieter and smaller than the present shipboard systems. Its efficiency, while comparable, is not better, although with the rapid strides recently made in the field of MHD systems, it is almost certain to improve in the near future. Likewise, the materials problem currently limiting high temperature systems is now being resolved with dispatch.

Chapter V

CONCLUSIONS AND RECOMMENDATIONS

Both MHD systems studied are attractive primarily because of the vast prospects for future developments and for ships because of the anticipated large reduction in radiated noise. The gas Brayton cycle can be used efficiently only as an electrical D-C power source, while the liquid-metal Rankine cycle can be used as either an A-C or a D-C source. If D-C is used in either cycle, low terminal voltages must be acceptable (particularly with the Rankine cycle). If A-C is used, suitable induction generators must be provided, and it is suggested that more efforts along this line are needed.

Both MHD systems studied showed theoretical efficiencies comparable with present steam turbine systems. Caution is to be used when comparing these efficiencies, as many very liberal assumptions were necessary to conduct the analyses, though future developments may more than compensate for these assumptions. In the gas Brayton cycle, the refrigeration requirement of the large superconducting magnet was not included, and it is feared that the power necessary for this would reduce the overall efficiency below acceptable levels. Furthermore, there is some question as to whether the fluid used (helium in this study) could develop the required electrical conductivity despite the seeding and non-equilibrium techniques used. Thus, it is recommended that extra exertion toward increasing the electrical conductivities of the present working fluids be made before further considerations of this cycle are attempted.

In the liquid-metal Rankine cycle, the electrical conductivity of the working fluid of the studied cycle again proved to be a problem because

the cycle chosen for investigation dealt with a two-phase MHD generator. Assumptions were made concerning the conductivity of the two-phase flow which may prove to be in error after future examinations of these flows are completed. The studied cycle utilized a mixture quality of 1.0 at the entrance to the nozzle, which could be reduced at the expense of poorer thermodynamic cycle performance, to decrease the mixture quality in the MHD generator and increase the performance of the generator because of the higher conductivity of the fluid. Thus, there appears to be a "happy medium" for the mixture quality which only further experimentation with the two-phase flows can resolve.

Since only one of the Rankine cycles described was investigated in detail here, it seems worthwhile to examine the others. In fact, because the other two liquid-metal cycles do not have the problem of two-phase flow through the MHD generator, they may turn out to be much better than the one-component, two-phase cycle investigated in detail in this thesis. There also exists the possibility of an entirely new cycle utilizing, for instance, the better parts of the three liquid-metal cycles discussed here. Thus, more studies are needed concerning these items before an attempt at "optimizing" is tried.

In conclusion, it is suggested that the possibility of this type of power generation system replacing steam turbines is high and that now is the time to initiate further studies aimed at achieving more practical results than are now possible.

Appendix I

Brayton Cycle MHD Generator Analysis

A. Constant temperature, constant current density analysis yields the following results:

(1) $\rho_2/\rho_1 = p_2/p_1 = \exp\left(\frac{(1 - K)(v_2^2 - v_1^2)}{2g^K RT}\right)$

(2) $A_1/A_2 = (v_2/v_1)(p_2/p_1)$

(3) Generator length, L, as calculated from the energy equation, is

$$L = \frac{-\rho_1}{\lambda}\left(\exp(-\zeta v_1^2)\right)\int_{v_1}^{v_2} v^2 \exp(\zeta v^2)\, dv$$

where $\lambda = JKvB$ and $\zeta = (1 - K)/2kgRT$

(4) The entropy rise, ΔS, is given by

$$S_2 - S_1 = -gR\ln \frac{p_2}{p_1}$$

(5) For the velocity and magnetic field, solve simultaneously the density and energy equations as follows:

(a) $(1 - K)vB = \text{constant}$ (from current density)

(b) $JB = -\frac{\rho}{K} v \frac{dv}{dy}$ (from energy)

B. Constant velocity, constant current density yields the following results:

(1) $p_2/p_1 = (T_2/T_1)^{\Upsilon}$

(2) $A_1/A_2 = \rho_2/\rho_1 = (T_2/T_1)^{\Upsilon}$ where $\Upsilon = \gamma/K(\gamma - 1)$

(3) $S_2 - S_1 = gR\Upsilon(1 - K)\ln \frac{T_1}{T_2}$

(4) $B = J/v(1 - K)\sigma = \text{constant}/\sigma$ where σ is a function of temperature determined experimentally

Appendix II

Calculation Procedures

for the Brayton Cycle Thermodynamic States

A. Process 0 - 1. Isentropic expansion through the nozzle

T_0, p_1, and v are known.

(1) $T_1 = T_0 - v^2/2gC_p$

(2) $p_0 = p_1\left(T_1/T_2\right)^{\frac{\gamma-1}{\gamma}}$

(3) $S_1 = S_0$

B. Process 1 - 2. MHD generator

(1) T_2 must be large enough to provide minimum conductivity and in this case is the value which provides enough power to drive the compressor at approximately one-half of the total generator output. (i.e. T_2 is thus still unknown at this point until the compressor power has been established in process 4 - 5).

(2) $p_2 = p_1\left(T_2/T_1\right)^{\frac{\gamma}{K(\gamma-1)}}$

(3) $S_2 = S_1 + \frac{gR\gamma(1-K)}{K(\gamma-1)} \ln \frac{T_1}{T_2}$

C. Process 2 - 3. Nonisentropic adiabatic diffusion.

η_d = diffuser efficiency

(1) $T_3 = T_2 + v^2/2gC_p$

(2) $p_3 = p_2\left(1 + \frac{\eta_d v^2(\gamma-1)}{2gR\gamma T_2}\right)^{\frac{\gamma}{\gamma-1}}$

(3) $S_3 = S_2 + gC_p\left(\ln\frac{T_3}{T_2} - \frac{(\gamma-1)}{\gamma}\ln\frac{p_3}{p_2}\right)$

D. Process 3 - 4. Constant pressure cooling.

(1) T_4 = minimum temperature allowed at outlet of heat exchanger due to cooling environment.

(2) $p_4 = p_3$

(3) $S_4 = S_3 + gC_p \ln\frac{T_4}{T_3}$

E. Process 4 - 5. Adiabatic compression

η_c = compressor efficiency

(1) $T_5 = T_4 + (T_{5i} - T_4)/\eta_c$ where $T_{5i} = T_4(p_5/p_4)^{\frac{\gamma-1}{\gamma}}$

(2) $p_5 = p_0$

(3) $S_5 = S_4 + gC_p \left(\ln\frac{T_5}{T_4} - \frac{(\gamma-1)}{\gamma}\ln\frac{p_5}{p_4}\right)$

F. Process 5 - 0. Constant pressure heating.

(1) T_0 = maximum temperature of system determined by heat source.

(2) $p_0 = p_5 = p_1(T_1/T_2)^{\frac{\gamma-1}{\gamma}}$

(3) $S_0 - S_5 = gC_p \ln\frac{T_0}{T_5}$

Appendix III

Calculation Procedures

for the One-Component, Two-Phase Liquid-Metal MHD Cycle

A. Process 1 - 2, Isentropic expansion through the nozzle

η_n = nozzle efficiency

T_1, p_1, S_1, X_1 known

(1) $S_1 = S_2$

(2) T_2 unknown - found by knowing value of T_4 and working back

(3) p_2 found from T_2

(4) X_2 found from entropy relation after finding T_2

(5) $v_2 = \left(\eta_n(h_2 - h_1)\right)^{\frac{1}{2}}$

B. Process 2 - 3. Generator

η_g = efficiency of generator (ratio of actual velocity squared to the ideal velocity squared)

(1) $T_2 = T_3$

(2) $p_2 = p_3$

(3) $X_2 = X_3$

(4) Output $= \eta_g(v_2^{\,2} - v_1^{\,2})/2g$

C. Process 3 - 4. Condenser

T_4 known

(1) p_4 = saturation pressure at T_4

(2) $p_3 - p_4$ assumed = 10 psi

(3) $X_4 = 0$

(4) $v_4 = v_3$

D. Process 4 - 5. Adiabatic diffusion

η_d = diffuser efficiency

(1) $T_5 = T_4$

(2) $v_5 = 0$

(3) $p_5 = p_4 + (\eta_d \rho_4 v_4^2)/2g$

E. Process 5 - 1. Heating

(1) $p_5 - p_1$ assumed = 10 psi

(2) Input = $h_1 - h_5$

Appendix IV

Calculation Procedure

Used for Determining the Electrical Conductivity of the Two-Phase Fluid

Since this is a subject about which little is known, the assumptions used for this procedure were derived largely from the experimental evidence of reference (27) in which the two-phase conductivity was found to approximate the emperical relation

$$\sigma_{TP} = \sigma\left(\frac{(1-\alpha)^2}{(1+\alpha)}\right)$$

where α is the void volume fraction, and σ is the liquid's conductivity.

The void volume fraction was then computed from the relation[35]

$$\bar{\rho} = \alpha\rho_V + (1-\alpha)\rho_L$$

where $\bar{\rho}$ is the mean density.

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